

Power Aware Based on Voltage Islands for X-Clock Tree Construction

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Abstract—This paper proposes an algorithm of power aware based on voltage islands for constructing an X-clock tree with considering double via insertion. Different voltages are assigned for multiple voltage islands for power aware to reduce total power consumption under the clock delay control. Higher rate of double via insertion is made for via-effect avoidance and reliability. We first partition a clock network to be the number of voltage islands, such as L-type or T-type, and construct the X-clock tree for each voltage island with double via insertion. Then, we combine these X-clock trees based on a well-defined connection with inserted level shifters for minimizing the power. The delay effect due to the total number of inserted double vias is also accounted. Ten benchmarks are tested for our approach. Compared with single voltage island, experimental results show that our X-clock tree based on multi-voltage islands can save up to 21.58%, 4.75%, and 33.8% in power, delay, and running time, respectively.

Index Terms—X-clock tree, voltage island, clock delay, power consumption.

I. INTRODUCTION

Reducing the power consumption is the critical issue in contemporary chip design for nano-meter process technology. A SoC (system-on a chip) integrates a number of functional blocks and usually has multi-mode operations for different set of blocks that work at different time [1]. If all the blocks are supported with a uniform supplying voltage, the power always consumed the same during all the working time. To save the power, the voltage-island design methodology [2]-[4] assigns multiple supplying voltages to the functional blocks in a system for minimizing power consumption. For instance, the performance-critical blocks, e.g. processors, require the highest supplying voltage and other noncritical-based blocks, e.g. control logics and peripheral units, can operate at lower voltages.

Signals are often required to transmit among the functional blocks of voltage islands via various buses or a clock at different time in a chip. We need to warrantee that these signals can be correctly transferred among voltage islands. For transmitting a signal on the different voltage islands, a level shifter (LS) has to be inserted into the interconnection that transmits a signal from a low-voltage island to a high one because a circuit may suffer from excessive leakage energy when low voltage gates directly drive high voltage ones [1], [4]. In a contrast, a level shifter is not required when a signal is transferred from a high-voltage island to a low one.

Many works for voltage islands were addressed. Lee *et al.* [5] proposed the voltage-island partitioning and floorplanning

under the control for timing constraints. Dong and Goto [6] presented the floorplanning approach based on the multi-voltage and level-shifter driven. A global routing for multi-voltage islands based on power-driven approach [7] was proposed for the evaluation of power reduction. Many literatures [8]-[13] were concentrated on single voltage island for clock tree construction. Tsai *et al.* [14] proposed a clock tree construction on multi-mode multi-voltage islands. Based on the binary clustering approach, they inserted buffers and adjusted their locations to minimize the clock delay and skew for matching different modes. Su *et al.* [15] and Lin *et al.* [16] improved the above approach by replacing some inserted buffers with adjustable delay buffers (ADB) for the well-defined control to the clock delay under boundary skew. Kim [17] expanded the clock tree synthesis to a 3D stacked IC. With the requirement of zero skew, the clock tree construction depends on the trade-off of TSVs and total wire length. The deferred layer embedding (DLE) is used for reducing the number of TSVs while the deferred merge embedding (DME) is employed for minimizing the total wire length. Chen *et al.* [18] proposed the 3D-IC clock tree that constructs the clock tree on ASIC layer to associate with the pre-defined clock network on platform layer. The TSVs on ASIC layer projected from the platform layer were controlled for minimizing the clock delay and skew. Lee *et al.* [19] extended the voltage islanding technique to apply for the concurrent optimization of power and temperature in 3D-stacked ICs. They adjusted the 2-layer 3D floorplanning to optimally partition several voltage islands for better hot stream for decreasing temperature.

In this paper, we propose an approach to construct an X-clock tree on multi-voltage islands. With the pre-defined partition for a clock network depending on the different supplying voltages, the clock tree for each voltage island can be individually constructed and they are then combined with associating level shifters to get the best one in trade-off of power and delay under zero skew. Compared with the original clock network (one island) from the experiments of proposed approach, we proved that our power consumption always get larger reduction under the reasonable clock delay.

The reminder of this paper is organized as follows. Section II describes the problem formulation. Section III states the power and delay estimation for a wiring model with level shifter and double via structures. Section IV presents the proposed algorithm of X-clock tree construction with considering double via insertion for power minimization. Experimental results running on benchmarks are shown in Section V followed by a conclusion of this work in Section VI.

II. PROBLEM FORMULATION

For a clock network problem with multiple islands using different supply voltages, generally, there are two straight

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approaches. The first one is to complete the whole clock tree routing, then insert level shifters in post-refinement step for minimizing the clock delay and compensating to be zero skew. Another approach is to reduce a routing problem to be a number of sub-problems. The approach first divides it to be multi-voltage islands and routes the subclock tree for each voltage island, then combine all the subclock trees to be a complete one with level-shifter insertion.

Fig. 1 shows an example for the explanation of above two approaches. As shown in Fig. 1(a), a chip consists of three voltage islands and twelve clock sinks. Islands 1, 2, and 3 respectively operate at 1.0 V, 1.1 V, and 1.2 V. Fig. 1(b) shows the first approach that the clock tree is directly constructed to connect twelve sinks located on three voltage islands. Six level shifters are required for interconnecting from the low-voltage island (Island 1) to other two high-voltage islands (Islands 2 and 3). Fig. 1(c) shows the second approach that the clock tree combines three subclock trees (CLK_1 , CLK_2 , and CLK_3) with two level shifters those respectively connect Island 1 (1.0 V) to Island 2 (1.1 V) and Island 3 (1.2 V). Compared with the first approach shown in Fig. 1(b), the second one can save four level shifters.

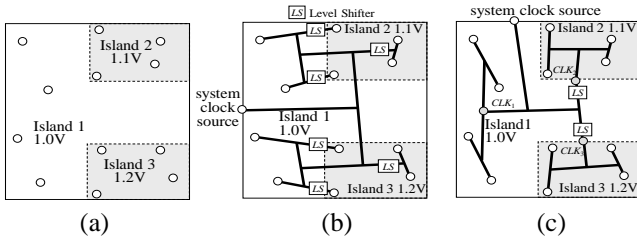


Fig. 1. Clock routings on (a) three voltage islands constructed from (b) approach A with six LSs and (c) approach B with two LSs.

We employ the second approach to construct a clock tree on multi-voltage islands. As shown in Fig. 1(c), the system clock source adopts the voltage of 1.0 V of Island 1 and two level shifters are required for driving Islands 2 and 3. That is, two subclocks CLK_2 and CLK_3 are first combined and then CLK_1 is integrated with two level shifters and them. On the other hand, we may select the voltage of 1.1 V of Island 2 as the supply voltage of system clock source, such that the subclocks CLK_1 and CLK_3 are first combined and a level shifter is inserted when CLK_2 is integrated with them. Based on the above discussion, we can estimate different combination of subclocks that constructs whole-chip clock routing with distinct inserted level shifters, power consumption, and clock delay. Experimentally, power consumption and clock delay are always trade off, that is, more power consumption more clock speed.

Due to the advanced lithography technologies, metal wires in a chip can be routed with arbitrary angles, especially for diagonal ($\pm 45^\circ$) wires assigned with metal layers 3 and 4. X-architecture combines diagonal, horizontal, and vertical wires to respectively achieve improvements of 10%, 20%, 30%, and 20% in terms of chip performance, power consumption, die cost, and wirelength compared with Manhattan-architecture [20]. Our clock tree construction considers this X-architecture.

Moreover, redundant-via insertion (RVI) is a well-known and effective method highly recommended by semiconductor foundries for reducing failed vias. As shown in Fig. 2(a), if via-open defect (v_2) exists and the clock signal cannot be

delivered to the clock sink s_i . RVI is also called double via insertion (DVI) because a redundant via r_i is inserted next to a single via v_i to form a double via structure, as shown in Fig. 2(b). When using the DVI method, we should follow the via width (v_w) and rule space (RS) to avoid creating any design-rule violation, as shown in Fig. 2(c). The double via insertion is also considered in our clock tree construction for improving yield and reliability.

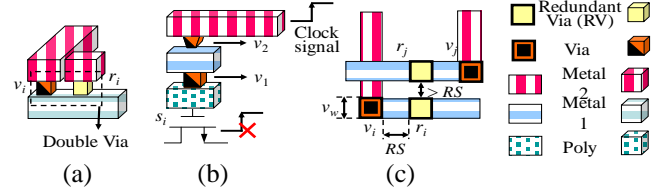


Fig. 2. (a) The cross-section view of a double via. (b) The clock signal cannot be delivered to clock sink s_i if a via (v_2) defects. (c) Design rules are for single and redundant vias.

In summary, our problem of clock routing on multi-voltage islands is defined as follows.

Given a set of clock sinks on a set of multi-voltage islands, the objective is to construct a zero-skew X-clock tree with considering double via insertion for power minimization.

Currently, no any papers contributed the clock tree construction based on X-architecture except our published PMXF approach of Tsai *et al.* [11] for constructing an X-clock tree. But, the approach just considered on the single voltage island with double via insertion. The purpose of this paper is to extend the work on multiple voltage islands to minimize the power consumption under the reasonable clock delay.

III. POWER AND DELAY ESTIMATION

To evaluate the power consumption of a clock tree based on single voltage island, the calculation of total power should include the equivalent wire capacitances of interconnections, input capacitances of inserted level shifters, and loading capacitances of multi-voltage islands. Thus, the total power P_{total} is formulated as follows.

$$P_{total} = \sum_{e_i} C_{load,i} F_{clk} V_{dd}^2, \quad (1)$$

where $C_{load,i}$, F_{clk} , and V_{dd} are the capacitance of the sink i (or node i), clock frequency, and supplying voltage, respectively. e_i is defined as the set of clock tree edges those are along the path from the clock root to the sink i .

The fitted Elmore delay (FED) model [21] is widely used for the wire delay calculation of a clock tree construction. A wire j with the width w_j and length l_j based on the FED model is shown in Fig. 3(a), where r , c_a , and c_f are the sheet resistance, unit area capacitance, and fringing capacitance, respectively. The delay of the wire j with a loading capacitance $C_{L,i}$ at the sink i is formulated as follows.

$$\text{Delay}(i) = (r l_j / w_j) [0.5(D c_a w_j + E c_f) l_j + F C_{L,i}], \quad (2)$$

where coefficients D , E , and F are obtained by using the curve fitting techniques [21].

A level shifter (LS) is used to insert into the interface from a low-voltage island to a high-voltage island. As reported in [1], a level shifter can consume the power and affect the delay. Fig. 3(b) shows that the equivalent circuit of a level shifter contains the intrinsic delay T_{LS} , input capacitance c_{LS} , and output resistance r_{LS} . When a level shifter drives the wire j

with a loading capacitance $C_{L,i}$ shown in Fig. 3(a), the delay is formulated as follows.

$$\text{Delay}(i) = T_{LS} + (r_{LS} + r_{l_j} / w_j) [0.5(Dc_a w_j + Ec_f) l_j + FC_{L,i}]. \quad (3)$$

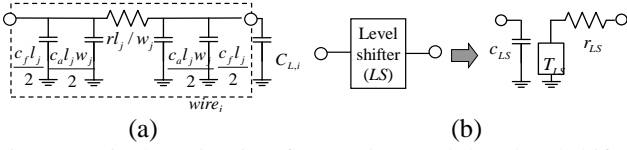


Fig. 3. Equivalent circuits of (a) a wire j and (b) a level shifter.

For a double via, the inserted redundant via is always parallel to the single via, as shown in Fig. 4(a). Hence, the resistance and capacitance of a double via are half and double of a single via, respectively. Fig. 4(b) shows the equivalent circuit of a double via, where k is two [20]. The delay calculation is referred the same to (2).

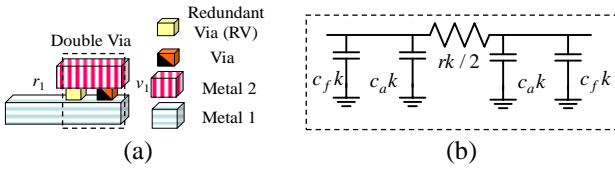


Fig. 4. (a) The cross-section view of a double via and (b) its equivalent circuit.

IV. ALGORITHM OF POWER AWARE BASED ON VOLTAGE ISLANDS FOR X-CLOCK TREE CONSTRUCTION

Depending on multi-voltage islands, each island can operate at a specified supplying voltage such that the total power consumption of a chip can be reduced. We propose an algorithm of multi-voltage-island-based X-clock tree construction with considering double via insertion (MuVIX-DVI) to integrate all the voltage-island X-clock trees for power minimization. Fig. 5 shows the proposed MuVIX-DVI algorithm.

Algorithm: MuVIX-DVI (Multi-voltage-island-based X-clock tree construction with double via insertion)
Input: A set of voltage islands VI and a set of supplying voltages SV
Output: A multi-voltage-island-based X-clock tree with considering double via insertion for power minimization.

- 1 $SV_{sys} \leftarrow$ Determine the supplying voltage of system clock source.
- 2 $PMXF(VI)$; /*construct X-clock tree for each voltage island $\in VI$.*/
- 3 $DVI-X$; /* Insert double via into X-clock tree for each voltage island $\in VI$.*/
- 4 Let each constructed X-clock tree be a leaf-node.
- 5 $CS(VI) \leftarrow$ Obtain the connection sequences of VI based on SV_{sys} .
- 6 for each voltage island $vi \in CS(VI)$
- 7 { $CS(LS) \leftarrow$ Obtain the connection sequences for level-shifter insertion.
- 8 do
- 9 { Make combination for each $ls \in CS(LS)$ }
- 10 while (power is improved)
- 11 }

Fig. 5. The proposed MuVIX-DVI algorithm.

In the algorithm, given a set of multi-voltage islands, VI , and a set of supplying voltages, SV , the supplying voltage denoted as SV_{sys} for the system clock source is first determined. Then, our one algorithm PMXF [11] constructs the X-clock tree for each voltage island belonging to VI and another algorithm DVI-X [12] is applied to the tree for inserting double via to improve yield and reliability. Third, we mark these constructed X-clock trees to be leaf nodes. To

integrate these leaf nodes of island-based X-clock trees for power minimization, all the connection sequences with different voltage islands can be combined as possible, denoted as $CS(VI)$. For a connection sequence $vi \in CS(VI)$ associated with the SV_{sys} of these islands, level shifters are required to insert into the interface from low-to-high voltage islands. The combination of connection sequences with level-shifter insertion is denoted as $CS(LS)$. After that, we estimate the power consumption for each connection sequence $ls \in CS(LS)$. Finally, we can get a multi-voltage-island-based X-clock tree with the well-defined connection sequence for minimum power consumption.

A. Determination of System Clock Supplying Voltage

Before constructing the system clock tree which connects all the island-based subclock trees, we first define the supplying voltage SV_{sys} for the system clock source as follows.

$$SV_{sys} = \min_{\forall vi_k} SV_k \quad (4)$$

For each voltage island $vi_k \in VI$, vi_k can operate at several supplying voltages $SV_k = \{sv_1, sv_2, \dots\}$. In this work, we set the lowest supplying voltage of all the voltage islands as the SV_{sys} for the expectation of minimum power consumption, but some level shifters should be required for the interfaces from low-to-high voltage islands.

B. PMXF: X-Clock Tree Construction on Single Voltage Island

We apply our PMXF algorithm [11] to construct an X-clock tree for each voltage island. Fig. 6 shows the outline of PMXF algorithm and the detailed information is referred in [11] due to limited space. An example of X-clock tree construction with 8 sinks, $s_1 \sim s_8$, using PMXF algorithm is shown in Fig. 7.

Algorithm: PMXF (Pattern-Matching X-architecture clock routing with X-Flip)
Input: A set of n clock sinks S and an X-pattern library for a pair of points
Output: An X-architecture clock tree with zero-skew and minimal delay

- 1 for $h \leftarrow 0$ to $\lceil \log_2 n \rceil$
- 2 while(un-paired-node in S_h) /* Check $|S_h| > 1$ or not.*/
- 3 $(s_i, s_j) \leftarrow DPPG(S_h)$; /*Determine a pair of sinks/points with GMA.*/
- 4 $PMX(s_i, s_j)$; /*Select the X-pattern of s_i and s_j .*/
- 5 $P_t \leftarrow DCTP(s_i, s_j, PTN(s_i, s_j), x)$;
/*Obtain tapping point P_t and zero-skew ratio x of (s_i, s_j) .*/
- 6 $X-Flip(s_i, s_j)$; /*Use X-Flip technique to reduce wire length of (s_i, s_j) .*/
- 7 if ($x < 0$) $WireSizing(s_i, s_j)$; /*Size wire width w_j .*/
- 8 if ($x > 1$) $WireSizing(s_j, s_i)$; /*Size wire width w_i .*/
- 9 $Insert(S_{h+1}, P_t)$; /*Insert P_t into the set of points at the $(h+1)^{th}$ level.*/

Fig. 6. The PMXF algorithm constructs an X-clock tree for each voltage island.

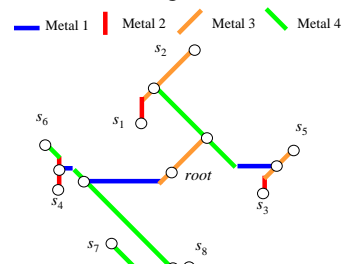


Fig. 7. An example of X-clock tree with 8 sinks.

C. DVI-X: Double Via Insertion for X-Clock Tree

Our DVI-X algorithm [12] is suitable for double via insertion to an X-clock tree. Fig. 8 shows the outline of DVI-X algorithm and the detailed information is referred in [12] due to limited space. Examples of X-clock tree partial layout before and after double via insertion are respectively shown in Figs. 9(a) and 9(b).

Algorithm: DVI-X (Double-via insertion for X-architecture clock routing)

Input: An X-architecture clock routing with the sets of wires W and vias V

Output: An X-architecture clock routing with double-via insertion

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1  $R = \text{ARVC}(V, W);$  /* Arrange redundant-via candidates (RVCs). */
2  $P = \text{Partition}(V, R);$  /* Make partitions with the intersecting RVCs. */
3 for each  $p_i(V_i, R_i) \in P$ 
4    $G_{b,i} = \text{CBG}(p_i);$  /* Construct bipartite graph  $G_{b,i}$  of  $p_i$  where  $G_{b,i} = (V_i \cup R_i, E_i)$ . */
5    $G_{c,i} = \text{CCG}(R_i);$  /* Construct the conflict graph  $G_{c,i}$  of  $R_i$  where  $G_{c,i} = (R_i, E_{c,i})$ . */
6    $C_{\max,i} = \text{MCQ}(G_{c,i});$  /* Obtain the set of maximal cliques  $C_{\max,i}$  of  $G_{c,i}$ . */
7    $M_i = \text{MBGC}(G_{b,i}, C_{\max,i});$  /* Match  $G_{b,i}$  and  $C_{\max,i}$  to insert double vias into  $p_i$ . */
    
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Fig. 8. The DVI-X algorithm is for inserting double via into X-clock tree.

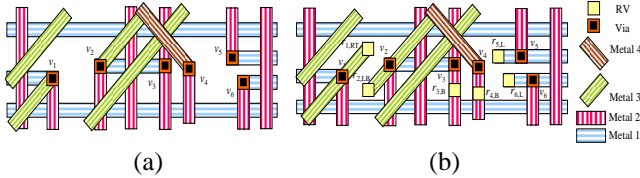


Fig. 9. An example of X-clock partial layout, the layout (b) is after inserting double vias into the layout (a).

D. Combination of X-Clock Trees among Voltage Islands

From the above two subsections 4.B and 4.C, given a chip with several voltage islands as shown in Fig. 10(a), PMXF first constructs the X-clock subtree for each voltage island and then DVI-X inserts double via into the subtree. Fig. 10(b) shows the X-clock subtree for Island 2. A system clock source enters the clock source CLK_2 of Island 2 to drive all the clock sinks synchronously. Here, we let its clock source CLK_2 be a leaf-node, denoted as Leaf-node_2 , and present its supplying voltages as $\text{SV}_2 = \{\text{sv}_1, \text{sv}_2, \dots\}$. Similarly, Leaf-node_3 and SV_3 respectively represent the clock source and supplying voltage of Island 3.

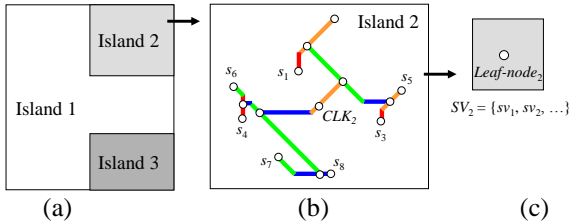


Fig. 10. (a) Given three voltage islands and (b) PMXF and DVI-X construct the X-clock subtree of Island 2 with double via insertion and (c) its subtree is labelled as a leaf node.

To construct a multi-voltage-island-based X-clock tree, we should know how to connect these islands with different supplying voltages to achieve minimum power consumption. Since the construction of X-clock tree is based on binary tree structure, the combination of connection sequences is $k!$ if there is a number of k leaf nodes. For the three voltage islands shown in Fig. 10(a), they are labelled as Leaf-node_1 for Island 1, Leaf-node_2 for Island 2, and Leaf-node_3 for Island 3 with three supplying voltages 1.0 V, 1.1 V, and 1.2 V, respectively. Hence, there are six connection sequences (i.e., $3!$), denoted as $\text{CS}(\text{VI}) = \{\text{vi}_1, \text{vi}_2, \text{vi}_3, \text{vi}_4, \text{vi}_5, \text{vi}_6\}$. For $\text{vi}_1 \in \text{CS}(\text{VI})$ as

shown in Fig. 11(a), Leaf-node_1 and Leaf-node_2 are connected first and then they are associated with Leaf-node_3 to complete the voltage-island-based X-clock tree. Fig. 11(b) shows the other connection sequence of $\text{vi}_6 \in \text{CS}(\text{VI})$.

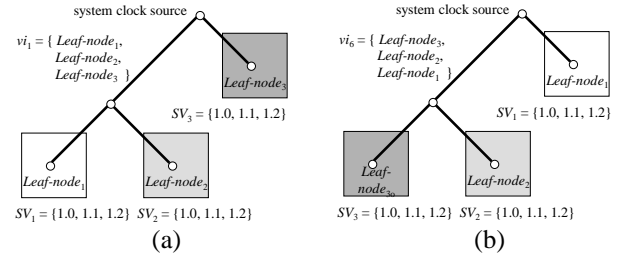


Fig. 11. (a) The first connection sequence vi_1 and (b) the sixth one vi_6 .

After determining the supplying voltage for the system clock SV_{sys} and the supplying voltage V_{dd} for each island, such as $\text{SV}_{\text{sys}} = 1.0 \text{ V}$, $V_{dd1} = 1.0 \text{ V}$, $V_{dd2} = 1.1 \text{ V}$, and $V_{dd3} = 1.2 \text{ V}$, we can integrate a multi-voltage-island-based X-clock tree with combining three leaf-nodes and inserting the required level shifters. For $\text{vi}_1 \in \text{CS}(\text{VI})$ shown in Fig. 12(a), the SV_{sys} is 1.0 V due to Islands 1-3 respectively operate at 1.0 V, 1.1 V, and 1.2 V. The inserted level shifters LS_1 and LS_2 deliver the system clock source at 1.0 V to Leaf-node_3 and Leaf-node_2 at 1.2 V and 1.1 V, respectively. This is the connection sequence for vi_1 with level-shifter insertion. On the other hand, Figs. 12(b) and 12(c) show the other two connection sequences for vi_6 with different level-shifter insertion. In Fig. 12(c), LS_1 delivers the system clock source at 1.0 V to Leaf-node_2 at 1.1 V and LS_2 that converts the clock signal from 1.1 V to 1.2 V. Hence, each connection sequence of multi-voltage islands has at least one connection sequence with level-shifter insertion.

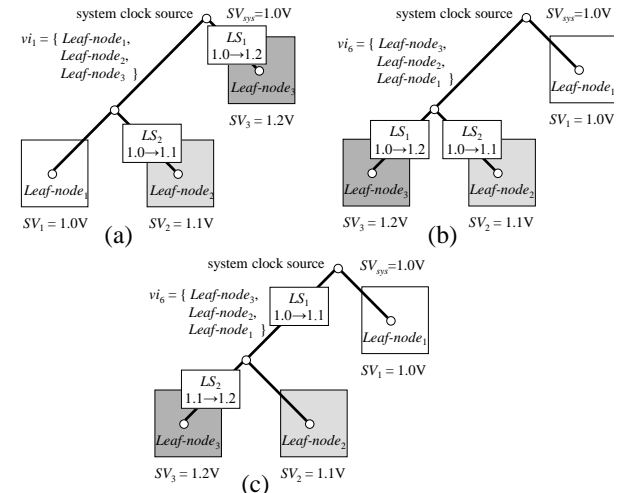


Fig. 12. The connection sequences with inserted level shifters for (a) vi_1 , as well as, (b) and (c) for vi_6 .

E. Power and Delay Estimation with Inserted Level Shifters

When the clock signal is delivered from a voltage island operating at SV_{sys} to another island which supplying voltage is higher than SV_{sys} , a level shifter has to be inserted. Fig. 13(a) shows that Islands 1 and 2 operate at 1.0 V and 1.1 V, respectively. When two islands are connected, a level shifter is inserted and delivers the clock signal from the system clock source to the Leaf-node_2 of Island 2. To respectively calculate the clock delay from the system clock source to Leaf-node_1 and Leaf-node_2 with (2) and (3), Fig. 13(b) shows the equivalent model of Fig. 13(a) based on FED model.

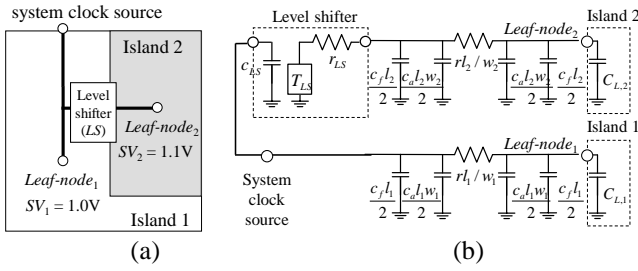


Fig. 13. (a) Two connected voltage islands with level-shifter insertion and (b) their equivalent circuit for delay calculation.

With the above discussion, different connection sequences with inserted level shifter should result different clock delays. At the same time, different power consumptions based on the calculation of (1) can also be obtained. Finally, we get the one with power minimization under the reasonable clock delay.

F. Analysis of Time Complexity

For given a set of n clock sinks in a set of m voltage islands, the proposed MuVIX algorithm shown in Fig. 5 can complete the design of multi-voltage-island-based X-clock tree. PMXF [11] constructs the X-clock tree for each voltage island in $O(n \log n)$. DVI-X [12] inserts double vias for each voltage island in $O(k^3)$, where k is the number of single vias. For each connection sequence, it takes $O(m \log m)$ to combine m leaf-nodes with inserted level shifters. Because we always determine the lowest supplying voltage as the supplying voltage for the system clock source, the combination of connection sequences for searching the minimum power consumption is less than $m!$. Moreover, $m \ll n$, $m \ll k$, and k is proportional to n . Hence, the time complexity of MuVIX algorithm is $O(n \log n) + O(k^3)$.

V. EXPERIMENTAL RESULTS

The proposed MuVIX algorithm of power aware based on voltage islands for X-clock tree construction has been implemented by using C/C++ programming language and performed on a MS-Windows 8.1 machine with Intel i7 CPU@2.2GHz, dual cores, and 8GB RAM. Table I lists the fabrication parameters of FED delay model [21] and level shifter (LS) under 130nm process [22] for power and delay calculation. The tested benchmarks contain IBM r1-r5 [8], ISCAS89 s1423, s5378, and s15850 [9], and MCNC Primary1-2 [10].

Table I. Technology parameters of FED delay model [21] and a level shifter [22] under 130nm.

r ($\Omega/\mu\text{m}$)	0.623	D	$1.12673\ln 2$	r_{LS} (Ω)	250
c_d (fF/ μm)	0.00598	E	$1.10463\ln 2$	C_{LS} (fF)	23.5
c_f (fF/ μm)	0.043	F	$1.04836\ln 2$	T_{LS} (ps)	54.4
				F_{clk} (Hz)	100M

For all the experiments, a benchmark is first partitioned into two voltage islands (i.e., L-type) or three voltage islands (i.e., T-type1 or T-type2) and the X-clock tree is constructed for each partitioned voltage island using PMXF algorithm [11] and then DVI-X algorithm [12] is followed for double-via insertion with considering the skew tuning for skew minimization. After the X-clock tree construction with double via insertion for each partitioned voltage island, we expand the PMXF algorithm to integrate all the island-based sub-X-clock trees and level shifters are inserted if the clock signal is delivered from a low-voltage island to a high-voltage island. Thus, we have several different connections depending on a sequence of islands associated with different

supplying voltages and level shifters. Finally, we can determine one of them that power consumption is minimized under the reasonable clock delay. Fig. 14 presents the platform of PMXF integrated environment for executing above experiments.

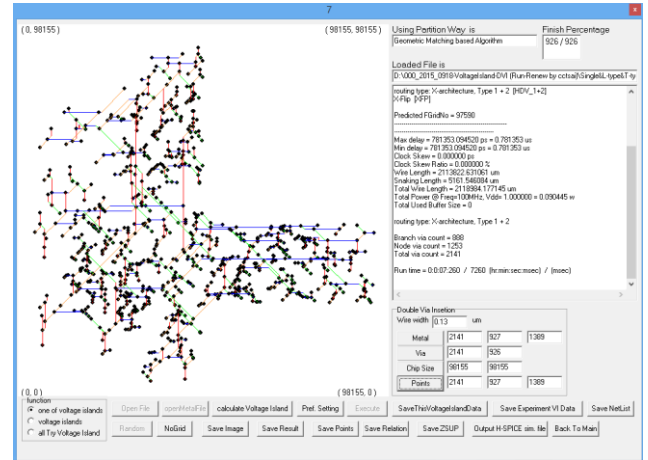


Fig. 14. The platform of PMXF integrated environment.

Fig. 15 shows three partitioned types, L-type, T-type1, and T-type2, for a benchmark. An L-type consists of two voltage islands, island 1 for 1.0 V and island 2 for 1.2 V, and the height of island 2 may be varied in the range of $1/2 \sim 2/3 h$, where h is the height of a benchmark. A T-type1 consists of three voltage islands, island 1 for 1.0 V, island 2 for 1.1 V, and island 3 for 1.2 V, and the height of island 2 or island 3 may be changed in the range of $1/3 \sim 2/3 h$. A T-type2 consists of three voltage islands, island 1 for 1.0V, island 2 for 1.1 V, and island 3 for 1.2 V, and the height of island 2 or island 3 may be varied in the range of $1/4 \sim 2/3 h$.

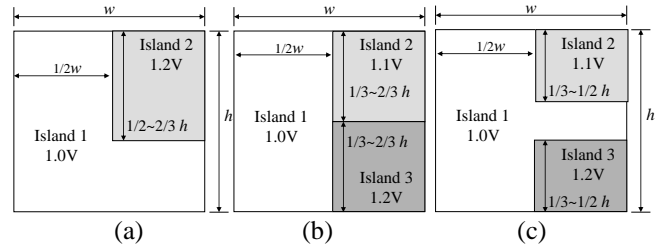


Fig. 15. The partition of (a) L-type, (b) T-type1 voltage islands, and (c) T-type2 voltage islands.

Table II shows the results of single voltage-island-based X-clock trees with/without considering double via insertion in terms of via, power consumption, clock delay, and CPU time. From the experiments, the rate (#Dvia / #via) of double via insertion (DVI) is up to 91.81% on average. This higher DVI rate can improve yield rate and reliability during process manufacture. The power and delay with double via insertion (wDVI) are always light larger than those of without double via insertion (woDVI). The ratio (wDVI / woDVI) in the table is defined as the power (delay) with vs. without considering DVI. In summary, the power and delay with DVI averagely increase 0.084% and 0.095%, respectively. The CPU time of PMXF is always larger than those of DVI-X and their CPU times are proportional to the number of sinks or inserted double vias.

Table III shows the comparison of L-type vs single voltage island with considering double via insertion. From the table, the power, delay, and CPU time using L-type can averagely save 21.85% (i.e., $1-0.7815$), 6.08% (i.e., $1-0.9392$), and 19.19% (i.e., $1-0.8181$), respectively, while the number of

vias is paying more 0.87% (i.e., $1.0087-1$).

Table IV shows the results of T-type1. Due to each benchmark is divided into three voltage islands and has different combined connections for the selection of different power and delay. The table present the three cases vs its single voltage island of a benchmark, lower power first, smallest delay first, and balanced power&delay first. From the table, we find that one of their three cases is not always best for all the benchmarks. Thus, the determined rule for the best one is that power consumption can be minimized as possible under the delay control. Therefore, each benchmark has the best one in power and delay marked in bold characters in the table. Similar results for another T-type2 are shown in Table V.

All the best results selected from Tables IV and V are listed in Tables VI and VII, respectively. We combine these results of Tables VI and VII and compare them to the results using single voltage island. The power, delay, and CPU time can averagely save 21.3% (i.e., $[(1-0.7939)+(1-0.7802)] / 2$), 3.43% (i.e., $[(1-1.0011)+(1-0.9304)] / 2$), and 48.4% (i.e., $[(1-0.4146)+(1-0.6175)] / 2$), respectively, while the number of vias is paying more 0.22% (i.e., $[(1.0002-1)+(1.0042-1)] / 2$).

Moreover, we compare all the results, the power, delay, and CPU time of multi-voltage islands (L-type+T-type) vs single voltage island that can save up to 21.58% (i.e., $(21.85\%+21.3\%) / 2$), 4.75% (i.e., $(6.08\%+3.43\%) / 2$), and 33.8% (i.e., $(19.19\%+48.4\%) / 2$) on average, respectively, while the number of vias is paying more 0.55% (i.e., $(0.87\%+0.22\%) / 2$).

Fig. 16 presents the X-clock trees of (a) L-type, (b) T-type1, and (c) T-type2 voltage islands with double via insertion for benchmark r5.

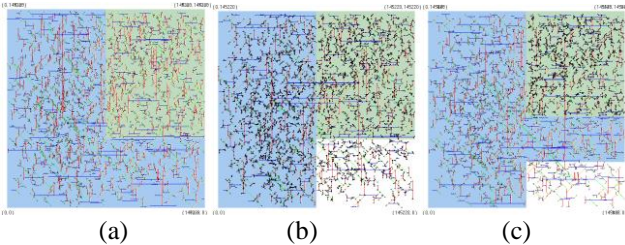


Fig. 16. X-clock trees of the benchmark r5 that are based on (a) L-type, (b) T-type1, and (c) T-type2 voltage islands.

VI. CONCLUSION

The X-clock tree construction with considering one of DFM issues, double via insertion (DVI), for via-effect avoidances and the DVI rate is always over 90% for reliable manufacturing. The modes of multi-voltage islands like L-type or T-type are implemented in the DVI-based X-clock tree construction in advance, the power consumption can be efficiently reduced as well as clock delay and running time compared with single one. Expanded work is to consider different partition models depending on different voltages and clock sink distribution on a 3D chip [17]-[19],[23] and integrate them to be a well-defined clock tree under control in power and delay.

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Table II. Results of single voltage island X-clock tree with/without considering double via insertion in via, power delay, and CPU time.

Benchmark	#Sinks	Vias in Single island			Power (mW) in Single island			Delay (ns) in Single island			CPU time (s) in Single island	
		#via	#Dvia	ratio	woDVI	wDVI	ratio	woDVI	wDVI	ratio	PMXF	DVI-X
<i>r1</i>	267	1222	1113	0.9108	80.12	80.237	1.00146	278.176	278.317	1.00051	35.71	0.374
<i>r2</i>	598	2840	2583	0.9095	194.889	195.091	1.00104	858.143	858.636	1.00057	163.9	1.357
<i>r3</i>	862	3995	3676	0.9202	261.838	261.996	1.00060	1452.224	1453.014	1.00054	29.68	2.574
<i>r4</i>	1903	9166	8401	0.9165	612.497	612.901	1.00066	4099.221	4101.838	1.00064	270.753	11.014
<i>r5</i>	3101	14665	13446	0.9169	1012.692	1013.366	1.00067	6934.2	6938.616	1.00064	974.752	28.314
<i>Primary1</i>	269	1195	1122	0.9389	169.068	169.102	1.00020	38.369	38.412	1.00112	2.92	0.375
<i>Primary2</i>	603	2335	2159	0.9246	417.055	417.13	1.00018	220.477	220.591	1.00052	16.98	1.42
<i>s1423</i>	74	350	323	0.9229	6.907	6.914	1.00101	6.507	6.518	1.00169	0.11	0.032
<i>s5378</i>	179	771	698	0.9053	17.549	17.569	1.00114	14.437	14.459	1.00152	4.53	0.203
<i>s15850</i>	597	2704	2475	0.9153	65.062	65.155	1.00143	43.441	43.517	1.00175	9.77	1.282
Average				0.9181			1.00084			1.00095		

Table III. Comparison of L-type vs single voltage-island X-clock trees with considering double via insertion in power, delay, and CPU time.

Benchmark	Total via			Power (mW)			Delay (ns)			CPU time (s)		
	Single island	L-type island	ratio	Single island	L-type island	ratio	Single island	L-type island	ratio	Single island	L-type island	ratio
<i>r1</i>	2335	2362	1.0116	80.237	59.901	0.7466	278.317	284.837	1.0234	16.056	3.705	0.2308
<i>r2</i>	5423	5453	1.0055	195.091	147.617	0.7567	858.636	853.203	0.9937	87.101	15.211	0.1746
<i>r3</i>	7671	7919	1.0323	261.996	211.568	0.8075	1453.014	1344.603	0.9254	16.347	18.034	1.1032
<i>r4</i>	17567	17843	1.0157	612.901	491.303	0.8016	4101.838	3011.99	0.7343	194.833	132.573	0.6804
<i>r5</i>	28111	26581	0.9456	1013.366	813.438	0.8027	6938.616	6377.82	0.9192	523.916	654.573	1.2494
<i>Primary1</i>	2317	2243	0.9681	169.102	129.026	0.7630	38.412	44.539	1.1595	2.489	2.492	1.0012
<i>Primary2</i>	4494	4373	0.9731	417.13	322.762	0.7738	220.591	150.233	0.6812	11.109	7.593	0.6835
<i>s1423</i>	673	705	1.0476	6.914	5.312	0.7683	6.518	6.147	0.9431	0.142	0.152	1.0704
<i>s5378</i>	1469	1608	1.0946	17.569	15.008	0.8542	14.459	13.571	0.9386	4.733	6.333	1.3381
<i>s15850</i>	5179	5145	0.9934	65.155	48.266	0.7408	43.517	46.732	1.0739	11.052	7.18	0.6497
Average			1.0087			0.7815			0.9392			0.8181

Table IV. Comparison of T-type1 vs single voltage-island X-clock trees with considering double via insertion in power and delay

Benchmark	Single island		Lower power first for T-type1				Smallest delay first for T-type1				Balanced power&delay for T-type1			
	P(mW)	Delay(ns)	P(mW)	ratio	Delay(ns)	ratio	P(mW)	ratio	Delay(ns)	ratio	P(mW)	ratio	Delay(ns)	ratio
<i>r1</i>	80.237	278.317	59.691	0.7439	427.582	1.5363	62.207	0.7753	288.858	1.0379	62.116	0.7742	299.385	1.0757
<i>r2</i>	195.091	858.636	148.002	0.7586	1250.522	1.4564	150.909	0.7735	921.493	1.0732	150.005	0.7689	1078.489	1.256
<i>r3</i>	261.996	1453.014	211.714	0.8081	1591.417	1.0953	217.006	0.8283	1336.342	0.9197	212.448	0.8109	1595.594	1.0981
<i>r4</i>	612.901	4101.838	488.249	0.7966	4708.278	1.1478	500.119	0.816	3539.556	0.8629	495.312	0.8081	3972.278	0.9684
<i>r5</i>	1013.37	6938.616	782.342	0.772	7953.024	1.1462	808.245	0.7976	7091.42	1.022	790.549	0.7801	7668.044	1.1051
<i>primary1</i>	169.102	38.412	132.392	0.7829	70.796	1.8431	135.808	0.8031	42.198	1.0986	135.332	0.8003	47.789	1.2441
<i>primary2</i>	417.13	220.591	319.622	0.7662	220.743	1.0007	333.061	0.7985	167.825	0.7608	329.334	0.7895	175.559	0.7959
<i>s1423</i>	6.914	6.518	5.179	0.7491	9.342	1.4333	5.44	0.7868	6.98	1.0709	5.44	0.7868	7.038	1.0798
<i>s5378</i>	17.569	14.459	13.535	0.7704	20.23	1.3991	14.112	0.8032	15.068	1.0421	13.992	0.7964	16.882	1.1676
<i>s15850</i>	65.155	43.517	48.224	0.7401	61.844	1.4211	50.532	0.7756	42.468	0.9759	50.397	0.7735	42.714	0.9815
Average				0.7688		1.3479		0.7958		0.9864		0.7889		1.0772

Table V. Comparison of T-type2 vs single voltage-island X-clock trees with considering double via insertion in power and delay

Benchmark	Single island		Lower power first for T-type2				Smallest delay first for T-type2				Balanced power&delay for T-type2			
	P(mW)	Delay(ns)	P(mW)	ratio	Delay(ns)	ratio	P(mW)	ratio	Delay(ns)	ratio	P(mW)	ratio	Delay(ns)	ratio
<i>r1</i>	80.237	278.317	59.851	0.7459	300.465	1.0796	65.776	0.8198	285.819	1.027	65.809	0.8202	285.82	1.027
<i>r2</i>	195.091	858.636	140.134	0.7183	823.275	0.9588	150.371	0.7708	630.627	0.7345	149.624	0.7669	631.169	0.7351
<i>r3</i>	261.996	1453.014	205.05	0.7826	1378.38	0.9486	216.096	0.8248	1160.669	0.7988	211.387	0.8068	1196.014	0.8231
<i>r4</i>	612.901	4101.838	479.296	0.782	3933.765	0.959	505.203	0.8243	3550.251	0.8655	494.468	0.8068	3624.769	0.8837
<i>r5</i>	1013.37	6938.616	768.672	0.7585	6424.236	0.9259	807.773	0.7971	5538.822	0.7983	790.973	0.7805	5612.758	0.8089
<i>primary1</i>	169.102	38.412	124.731	0.7376	57.195	1.489	131.744	0.7791	42.847	1.1155	130.898	0.7741	44.059	1.147

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<i>primary2</i>	417.13	220.591	308.293	0.7391	209.02	0.9475	327.941	0.7862	167.037	0.7572	324.382	0.7777	167.721	0.7603
<i>s1423</i>	6.914	6.518	5.31	0.768	8.317	1.276	5.815	0.841	5.799	0.8897	5.761	0.8332	5.871	0.9007
<i>s5378</i>	17.569	14.459	12.839	0.7308	15.598	1.0788	14.038	0.799	11.204	0.7749	13.887	0.7904	11.265	0.7791
<i>s15850</i>	65.155	43.517	48.416	0.7431	46.194	1.0615	52.137	0.8002	32.254	0.7412	52.051	0.7989	32.26	0.7413
Average				0.7506		1.0725		0.8042		0.8502		0.7956		0.8606

Table VI. Comparison of T-type1 vs single voltage-island X-clock trees with considering double via insertion in power, delay, and CPU time.

Benchmark	Total via			Power (mW)			Delay (ns)			CPU time (s)		
	Single island	T-type1 island	ratio	Single island	T-type1 island	ratio	Single island	T-type1 island	ratio	Single island	T-type1 island	ratio
<i>r1</i>	2335	2355	1.0086	80.237	62.207	0.7753	278.317	288.858	1.0379	16.056	2.664	0.1659
<i>r2</i>	5423	5398	0.9954	195.091	150.909	0.7735	858.636	921.493	1.0732	87.101	6.198	0.0712
<i>r3</i>	7671	7937	1.0347	261.996	217.006	0.8283	1453.014	1336.342	0.9197	16.347	6.838	0.4183
<i>r4</i>	17567	18322	1.0430	612.901	495.312	0.8081	4101.838	3972.278	0.9684	194.833	48.904	0.2510
<i>r5</i>	28111	27530	0.9793	1013.366	808.245	0.7976	6938.616	7091.42	1.0220	523.916	235.56	0.4496
<i>Primary1</i>	2317	2214	0.9556	169.102	135.808	0.8031	38.412	42.198	1.0986	2.489	1.723	0.6923
<i>Primary2</i>	4494	4285	0.9535	417.13	329.334	0.7895	220.591	175.559	0.7959	11.109	5.226	0.4704
<i>s1423</i>	673	662	0.9837	6.914	5.44	0.7868	6.518	6.98	1.0709	0.142	0.18	1.2676
<i>s5378</i>	1469	1560	1.0620	17.569	14.112	0.8032	14.459	15.068	1.0421	4.733	0.204	0.0431
<i>s15850</i>	5179	5110	0.9867	65.155	50.397	0.7735	43.517	42.714	0.9816	11.052	3.5	0.3167
Average			1.0002			0.7939			1.0011			0.4146

Table VII. Comparison of T-type2 vs single voltage-island X-clock trees with considering double via insertion in power, delay, and CPU time.

Benchmark	Total via			Power (mW)			Delay (ns)			CPU time (s)		
	Single island	T-type2 island	ratio	Single island	T-type2 island	ratio	Single island	T-type2 island	ratio	Single island	T-type2 island	ratio
<i>r1</i>	2335	2384	1.0210	80.237	65.776	0.8198	278.317	285.819	1.0270	16.056	4.818	0.3001
<i>r2</i>	5423	5533	1.0203	195.091	140.134	0.7183	858.636	823.275	0.9588	87.101	3.558	0.0409
<i>r3</i>	7671	7685	1.0018	261.996	205.05	0.7827	1453.014	1378.38	0.9486	16.347	8.444	0.5166
<i>r4</i>	17567	17486	0.9954	612.901	479.296	0.7820	4101.838	3933.765	0.9590	194.833	68.26	0.3504
<i>r5</i>	28111	28162	1.0018	1013.366	768.672	0.7585	6938.616	6424.236	0.9259	523.916	263.118	0.5022
<i>Primary1</i>	2317	2288	0.9875	169.102	131.744	0.7791	38.412	42.847	1.1155	2.489	2.676	1.0751
<i>Primary2</i>	4494	4597	1.0229	417.13	308.293	0.7391	220.591	209.02	0.9476	11.109	7.25	0.6526
<i>s1423</i>	673	651	0.9673	6.914	5.761	0.8332	6.518	5.871	0.9007	0.142	0.296	2.0845
<i>s5378</i>	1469	1519	1.0340	17.569	13.887	0.7904	14.459	11.265	0.7791	4.733	0.182	0.0385
<i>s15850</i>	5179	5129	0.9904	65.155	52.051	0.7989	43.517	32.26	0.7413	11.052	6.789	0.6143
Average			1.0042			0.7802			0.9304			0.6175